A Gaussian Beam Measurement Range for MM and Sub-MM Receivers

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Introduction

The European Space Agency Far Infra Red and Sub-millimeter Telescope, "Herschel Space Observatory" [1] - the mission formerly known as FIRST - is a corner-stone mission with the planned launch date in the year 2007. The Heterodyne Instrument for the Far-Infrared (HIFI) [2] of FIRST covers 470 to 1200 GHz frequency band with two additional bands around 1.6 and 1.9 THz. The Instrument that uses Gaussian beam optics (quasioptics), combines the beams from the receiver channel frontends and matches this multi-frequency, multi-element receiver to the main telescope mirror. The importance of the quasioptical system for the overall instrument performance is clearly understandable from the fact that it is placed between the receiver and the antenna, and therefore any (extra) loss will directly increase the system noise temperature and be detrimental to the entire instrument performance. In order to build this instrument the HIFI team needs a testing facility to characterize the beams of the mixer assemblies / subassemblies of the Heterodyne Instrument. The Instrumentation Group of the Onsala Space Observatory has committed and built such a testing setup for measuring the mixer sub-assemblies' beams. Besides the measurement of the input beam of the mixer subassembly (MSA), a basic unit of the HIFI receiver, the measurements should produce accurate data on the beam waist position and its size in absolute coordinate system referred to the MSA reference point. In order to achieve the required performance and obtain data on the waist position we use scalar method of measurement, which includes several scans across the axis of the receiver beam and further data processing to extract the waist size and position. The measurement procedure includes triangulation in order to couple the scanner-referenced coordinate system of the probing source to the reference installed on the mixer subassembly bracket situating at 4 K ambient temperature. To avoid interference of the measurements with vacuum cryostat window the entire measurements are done under vacuum. The system realization is described in details in [3, 4, 5].

Measuring Technique and Hardware

The general idea of the measurements is to move a probe source radiating within the band of the receiver under test (MSA) across its input beam, as it is shown schematically in Figure 1. The quantity that is then measured is the power-coupling coefficient [6]

$$|C_{21}|^2 = \iint dy dx\, E_{\mathrm{MSA}}(r)\, E^{*}{}_{\mathrm{Source}}(r)$$

where E_{MSA} and E_{Source} are the electric field amplitudes of the MSA and the Source.

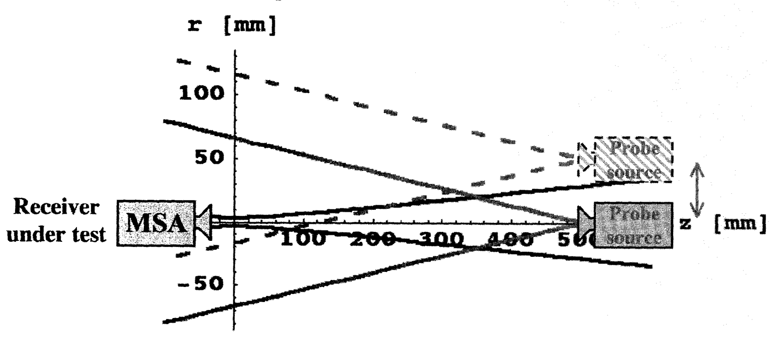

Figure 1. Illustration of the beam-profile measurement.

In order to provide all-in-vacuum measurements to avoid interference of the measuring with the vacuum windows and absorption of the probe signal in the air the entire measurement setup is placed into two vacuum vessels connected via a gate-valve of about 30 cm of diameter and having separate pumping facilities, Figure 2. The larger chamber contains a precision scanner employing hexapod mechanism, which is mounted on a linear stage with position accuracy of <40 μm in *x*-,*y*- and z-direction. On the centre of the hexapod platform, a probing source has been mounted. Using the hexapod, it can be moved in the *x-y* plane in few μm steps up to +/- 150 mm. Further rotational stages enable rotations of the source around the *x*- and *y*-axis up to angles of 20°. Movements along the *z*-axis, which coincides almost with the beam-axis, can be performed using the linear stage with high precision. Measurements of the beam can be done at distances between approximately 600 mm and 1050 mm from the beam waist. The source used for the first measurements was a Gunn-chain [7] operating at 480 GHz. The source was phase locked to external commercial synthesizer. The corrugated horn of the source was constructed to simulate a point-source [8]. To avoid overheating of the source, when operated in vacuum, cold nitrogen gas flashed through the pipe system and the source bracket providing the temperature controlled within 0.3° C. To diminish effects due to reflections, the larger vacuum-chamber walls are protected with plates covered by a combination of silicon-carbide grains and Stycast [9].

The second, smaller, vacuum-chamber contains a cryostat, which accommodates the MSA to be measured and, for the HIFI MSAs, the second stage cryogenic amplifier. The cryostat consists of a liquid nitrogen (LN_2) cooling stage at 77 K and a liquid helium (LHe) cooling stage at 4 K. The MSA itself is mounted on the bottom of the LHe cooling plate. Further, we used a grid to inject the LO signal into the MSA beam with LO-power transmitted through the grid dumped by an absorbing plate made also from Stycast and silicon carbide. During the measurements, when the cryostat is cooled down to 4K, the cryostat itself acts as a cryo-pump and the turbo-molecular pump can be turned off to avoid vibrations. Typical operational pressures are about 10^{-7} mbar.

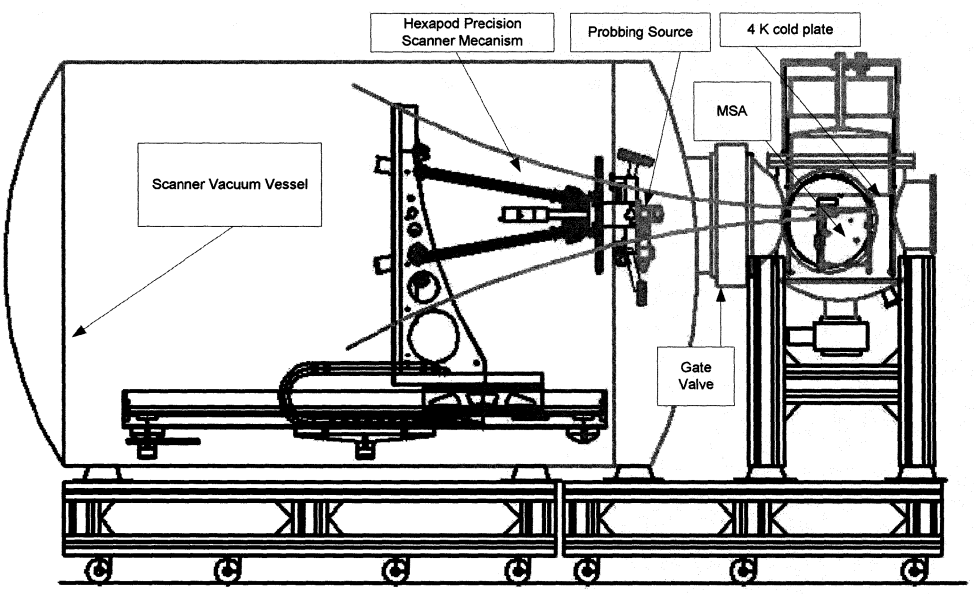

Figure 1. Setup of the measurement range for quasi-optical beam characterization at GARD.

The local oscillator itself is mounted outside the small vacuum chamber containing the MSA and coupled into the vacuum-chamber via a Teflon-window. For the measurements with DM of MSA band 1, a Carcinotron was used. The Carcinotron was operated at a frequency of 484 GHz, leading to an intermediate frequency (IF) of ~ 4 GHz. For the measurements of DM of MSA band 2, a backward-wave oscillator was used operated at a frequency of 644 GHz, leading also to an IF of ~4 GHz.

For absolute position determination, an in-house developed laser-triangulation system is used [3]. It consists of two diode-lasers and two PSDs mounted on the hexapod platform next to the source. A reference mirror is mounted on the bracket of the MSA,. The position of one corner of this rectangular mirror has been measured within µm accuracy with respect to the centre of the aperture for the input beam in the bracket holding the MSA. Using the triangulation system, the position of the hexapod with respect to the aperture in the MSA-bracket can be determined. A second mirror for calibration purposes is mounted on the linear stage of the hexapod. The positions of the second mirror and of the bracket holding the source were measured by the Swedish Metrological Institute using a laser-tracking system. During each cool-down of the MSA, the triangulation system is used to calibrate the hexapod against the position of the MSA. The level of overall accuracies reached with this laser-triangulation system are presently about 400 µm. However, accuracies of <300 µm in the direction transversal to the axis of beam-propagation should be feasible.

Measurement Results and Discussion

Several measurements were done testing the general response of the system and the repeatability. Furthermore, tests for standing waves and the stability of the system were performed. An example of the data for the test of standing waves is shown in Figure 3. Here, a scan along the *z*-direction (i.e., the axis of beam-propagation) was performed along 20 mm at an initial distance of about 780 mm from the beam-waist. The scan was performed at fixed *x*- and *y*-positions of x=-12 mm and y=8 mm, the approximate centre of the beam at this distance from the beam-waist. Several more scans were performed at different *x*- and *y*-positions and at different distances from the beam-waist. The results shown in Figure 3 show standing wave patterns due to the source or the LO which are of the order of 0.1 dB (at this *x, y* - position). The Fourier-transform of the signal, also shown in Figure 3, shows a peak at 32 cm^{-1}, which corresponds to 960 = 2x 480 GHz. This indicates that the origin for the standing waves are reflections in the signal-path of the source or the LO. To account for the standing waves, the measurements of planar scans, starting with the DM of MSA2 was done at two adjacent planes, which are shifted by a quarter of the corresponding wavelength, thus eliminating in the average the effect of standing waves.

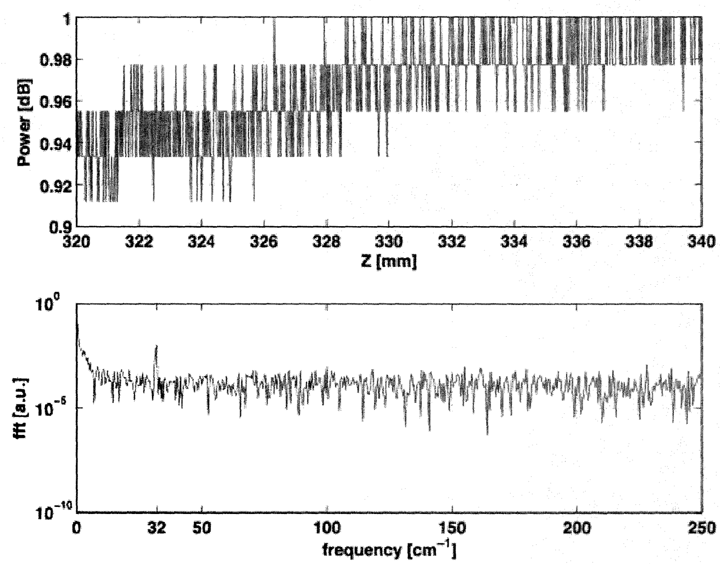

Figure 3. Standing wave test. The measurement for constant *x* and *y* along the *z*-axis, showing a standing wave ripples. In the upper plot, the measured data are shown, in the lower plot, the spectra (FFT) of those data.

Further tests were done of the overall signal stability, shown in Figure 4. This measurement was performed at a fixed position of the hexapod near the centre of the beam, while the power was monitored for about 30 minutes. The standard deviation here is about 0.1 dB, which is probably due to the free-running source of the LO signal. The Fourier-transform of the signal shows only white noise at a very low level.

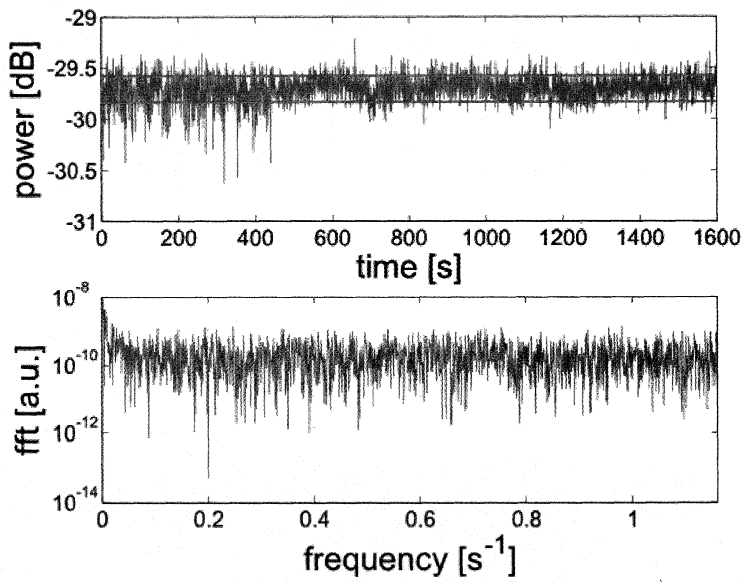

Figure 4. Stability test of the power at a fixed hexapod-position as a function of time (the upper plot). The lower plot shows the spectra (FFT) of the power stability data of the above plot.

In Figures 5 and 6, the contour plots of the raw measurements are shown for MSAs Band 1 and Band 2 respectively. For both bands, the maximum power of the beam profile was measured about 25-30 dB above the noise-floor. The contour plots show a Gaussian peak with a slight asymmetry in the *y*-direction. The measurement for MSA Band 1 shown in Figure 5 was performed at a distance of ~700 mm from the beam-waist. The measurements for MSA Band 2 shown in Figure 6 were performed at 622, 722 and 902 mm from the MSA-aperture.

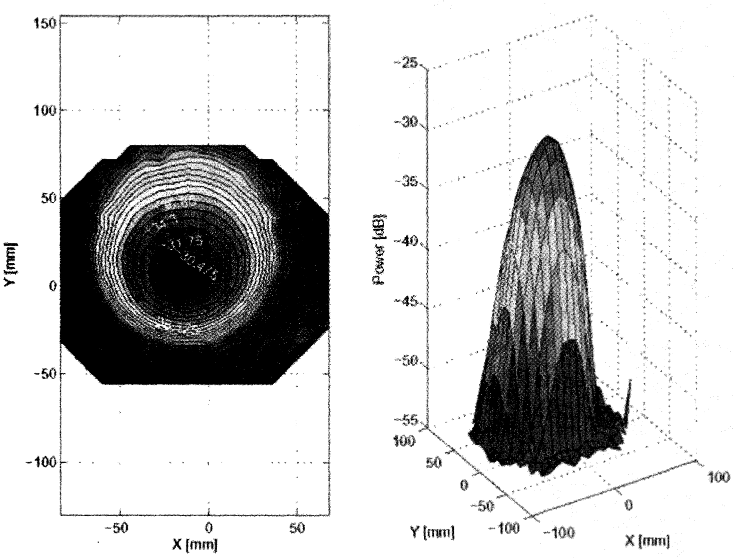

Figure 5. Beam-profile measured for the demonstration model of MSA band 1 about 700 mm from the position of the beam-waist.

For DM of MSA band 1, the direction of the beam-axis and the point of intersection of the beam-axis with the aperture-plane of the MSA bracket were determined from the data [4]. The calibration of the triangulation of those measurements was done using an external calibration mirror, which involved removing the bracket holding the source from the vacuum-chamber. The results apparently contain a systematic uncertainty due to the triangulation system, as has been observed by comparison to the measurements done at SRON [10]. For DM of MSA band 2, preliminary results for the beam axis and the intersection in the aperture plane were obtained. However, the internal calibration mirror is still being commissioned.

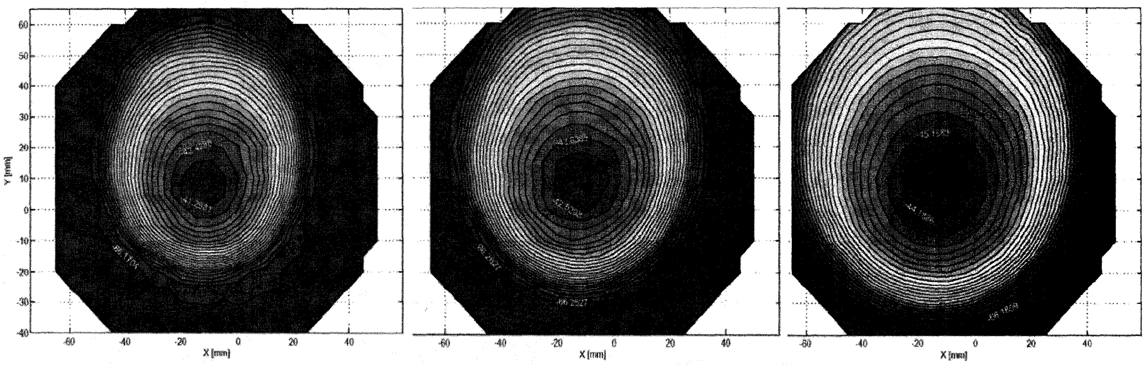

Figure 6. Beam-profiles measured for the demonstration model of MSA band 2 at distances (from left to right) of 620 mm, 720 mm and 900 mm from the beam-waist.

A general method for the measured data analysis is to fit fundamental Gaussian beam of the form

$$G(x,y) = a\exp\left\{-\frac{(x-x_c)^2}{\Delta x^2} - \frac{(y-y_c)^2}{\Delta y^2}\right\}$$

to the data, where the amplitude a, the central positions x_c, y_c and the widths Δx, Δy are the fitting parameters. An example of this fit is shown in Figure 7 .The central positions of the measured beam-profile at several distances from the beam-waist can be used for a three-dimensional line-fit of the axis of beam propagation. From the direction of the beam axis, the point of intersection at the MSA aperture can be determined. Furthermore, the angular deviations of the axis of propagation from the MSA mechanical axis can be determined. Unfortunately, this method is not sufficient to obtain the position or the size of the beam waist.

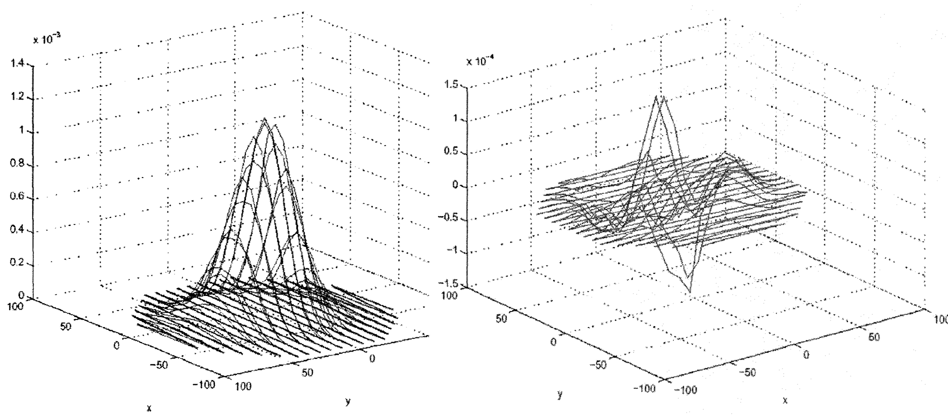

Figure 7. Gaussian fit to a planar scan about 720 mm from the beam-waist (left picture). Residuals of the fit at the right.

Conclusion

Gaussian beam measurement range has been built to provide possibilities to characterize the input beam of the mixer subassemblies for HIFI of Herschel Project. The beam measurement range is operational and has produced the first data. So far, measurements of the design-models of MSAs band 1 and 2 have been performed, using planar scans for a fixed z-coordinate of the probe-source from the MSA. Possible sources of errors, e.g., the standing waves and the measured power stability were calibrated allowing us 25-30 dB of the dynamic range. In order to achieve accurate reference in the MSA referred coordinate system the in-house developed laser-triangulation system was used. This triangulation system is still being commissioned to achieve ultimate accuracy.

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